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Electric Railway Traction

Railway Power Supply in France

ALTHOUGH electric operation of steam railways in France dates from 1900, it is only in post war years that extensive schemes have been put in hand. The activities in the last 15 years have been the result mainly of an effort to reduce the coal imports and utilise the country's natural resources, but as electrification on a large scale was contemplated the French Government appointed a commission to study the question of standardisation. The recommendations of this commission regarding the generation and supply of current for traction purposes were adopted in 1920, and since that year the use of 1,500 volt direct current (with 3,000 volts in special cases) has been compulsory for new electrified systems. It was further decided that traction power should be generated as three-phase 50 cycle current, in order to conform to the general standard for the supply for light and power. Practically all the electrification schemes which have been completed or considered in the last 25 years have taken account of the potential water power in the Pyrenees and the Massif Central, with the result that the whole of the power used by the Midi and the greater part of that used by the P.O. is generated in hydro-electric stations owned by these railways themselves. The Midi owns seven stations in the Pyrenees, but little more than half of the total output of 400 million kWh. is used for traction purposes, the remainder being distributed through the southern provinces for general purposes in conjunction with the current from other stations belonging to a corporation of power-producing companies. Similarly, the P.O. obtains practically all its current from its hydro-electric stations at Coindre and Eguzon, with a yearly production of 140 million kWh., but the power lines are tied in with those emanating from the big steam power stations, *e.g.*, that at Gennevilliers, in the neighbourhood of Paris.

Electrification and the Copper Industry

APART from electrical manufacturers, no branch of industry benefits to such a great degree from an electrification scheme as does that of copper. For instance, in the conversion of the Paris-Le Mans main line of the French State Railways and of certain Paris suburban lines of the Eastern Railway, 126 million fr. out of a total of 820 millions go directly to the copper industry. The main avenue into which the copper and its alloys are turned is in the tranmission and overhead systems, but a large amount is used in the fabrication of electrical apparatus for substations, control gear, traction equipment on the motive power units, and for feeding and bonding on low voltage direct current lines with third rails. For instance, 25,000 lb. of copper are used in a certain single-phase locomotive weighing 140 tons, and over three times this amount is incorporated in the triple-unit Virginian Railroad locomotive, the largest electric tractor in the world. Over 10,000,000 lb. of copper is used on the electrified system of the New York, New Haven & Hartford Railroad, which was described in the issue of this Supplement for July 27, and at the conclusion of its present programme the copper total of the Pennsylvania Railroad will amount to 90,000,000 lb. The power plants supplying current to the 2,200-odd route miles of electrified railway in the United States, are computed to contain 10,000,000 lb. of copper, the transmission lines 30,000,000 lb., the substations 6,000,000 lb., and the motive power 22,000,000 lb. Altogether, it is estimated that over 550,000,000 lb. of copper are used on the electrified railways of the world, but perhaps the best idea of the amount of copper used in big electrification programmes is gained from the fact that if the recommendations of the Weir Report for the electrification of British railways were carried out, something like 1,000,000,000 lb. of copper would be required.

A World Grid Scheme

AT the last World Power Conference a suggestion was made for the linking-up of large power plants at relatively tremendous distances apart with a view to equalisation of load over the whole 24-hr. period, the idea being to get power plants which are situated at different meridian distances in an east-west direction to cooperate systematically. An extreme case would be a power plant in eastern Asia working in conjunction with a plant in western Europe. Such plants would operate with a day and night displacement of 12 hr., although in the realm of absolute time no displacement exists. Night power in Europe could thus be transformed into day power in Asia. The author of the paper dealing with the possibilities of this scheme, Mr. H. Angstrom, of Sweden, considers that even a time displacement of two to four hours is enough to give a decided advantage. The Scandinavian power plants, for instance, are situated about 1,600 miles from those in the Ural district of Russia, which corresponds at the latitude of Stockholm to a time displacement of three hours. From Stockholm to Tomsk, in Siberia, is roughly 1,900 miles, and from there on to Pekin another 1,900 miles, corresponding in each case to a time of four hours by terrestrial rotation. Mr. Angstrom contends that with the present type of high tension transmission the linking up of places 2,000 miles apart is technically possible. Even under optimum conditions, when large consumers with similar great variations in day and night load, cooperate in order to increase the durance of the rated load, and thus increase the degree of utilisation of the fixed equipment, we are inclined to doubt whether the present state of the transmission art is advanced enough to make the scheme pay on a strictly financial basis. In any case, the technical side is of secondary importance. Even with the most peace loving countries acting together, there is always the possibility of future friction. The U.S.S.R., with its far-flung territory, is the only country in the world which could work upon a time interval of eight hours, but even in this case, the network suffers from the inherent defect of grids, *i.e.*, it is especially vulnerable in case of hostile attack, and any temporary mechanical or electric breakdown may effect a large area.

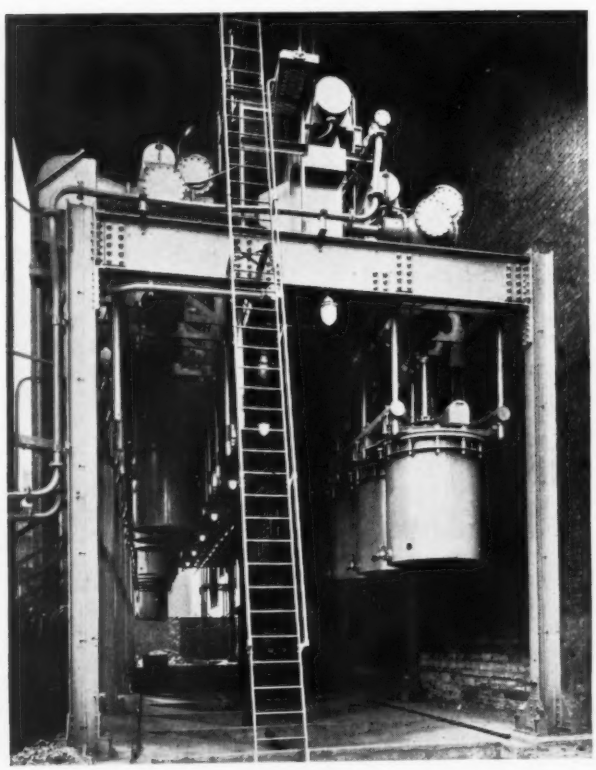
HIGH-VOLTAGE METAL-CLAD SWITCHGEAR

Notable improvements in design have been made in apparatus intended for use in confined spaces

THE very high voltages employed in the distribution of electrical energy over the National Grid have given rise to many peculiar problems, and particularly is this so in built-up areas where, owing to the high cost of land, transformer plant and switchgear can be given relatively little space. To meet the conditions encountered in London, where it was obvious that the normal type of gear for 66,000 volts could not be used, A. Reyrolle & Co. Ltd. developed an oil-immersed circuit breaker of a particularly compact type, and, after prolonged tests in the Hebburn works of the company, switchgear sets, each comprising a number of 3-phase groups, were erected at Stepney and Bankside. These installations have been in service approximately six months and are shown in the accompanying illustration.

The ordinary outdoor type of switchgear makes use of bare conductors and air insulation, but large gaps are necessary between adjacent conductors and between all conductors and earth. In the new Reyrolle gear all conductors are carried in earthed metal tubes or casings, insulation being effected by oil-impregnated paper and where necessary, by condenser bushings. The impregnation is guaranteed and all inflow of air is prevented by making the conductors tubular and running transformer oil under pressure through them. The desired head of oil

Fig. 1 (*above*) : *66 kV. circuit breakers at Bankside*
Fig. 2 (*left*) : *Circuit breakers at Stepney*
Fig. 3 (*below*) : *High voltage switchgear assembled for test*



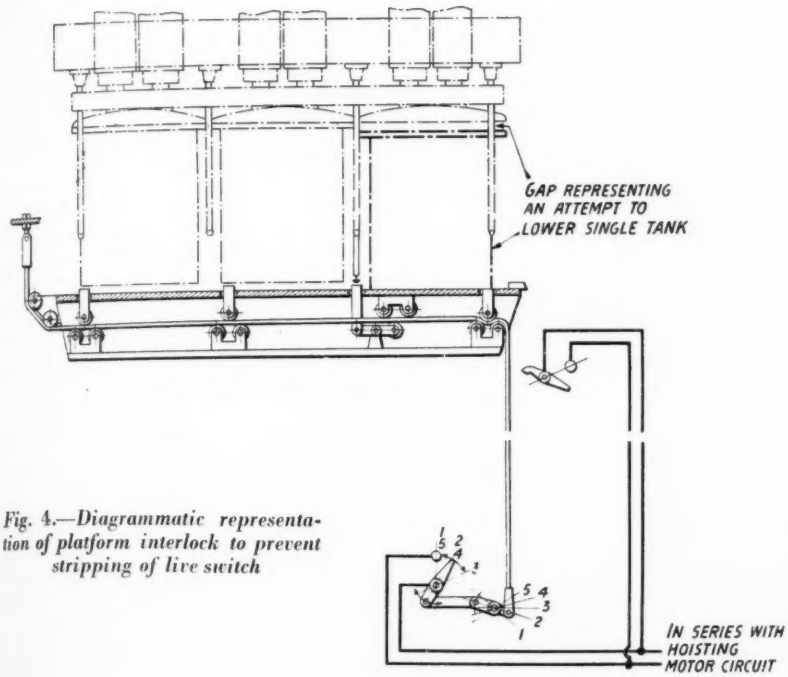


Fig. 4.—Diagrammatic representation of platform interlock to prevent stripping of live switch

is obtained by maintaining a predetermined level in the small cylindrical tanks seen at the top of the gear. A float operated alarm is contained in each tank to give warning when the levels fall too low. A very real advantage of the new metal-clad gear is that it can be cleaned and painted externally while actually in use, there being no possibility of shock at any point.

The switch contacts are enclosed in vertical cylindrical oil tanks, a tank for each phase, or three tanks per circuit breaker. The three tanks with their switches are carried beneath a pair of horizontal bars, and they form with these bars a unit which can be lowered bodily for maintenance work, or be transferred elsewhere. Normally it rests on cotters in six vertical rods, but when it is to be lowered its weight is taken by a truck with a rising platform. The cotters can then be withdrawn by hand and be re-inserted lower down in the six vertical guide rods, or, if the unit is to be taken away, they can be left out. In Fig. 2 the nearest unit on the right is shown resting on the cotters in their lower positions. The openings left, as the poles of the switch are withdrawn from above, are automatically covered by metal flaps so that even the most deliberate attempts to touch the live bus bars would be frustrated.

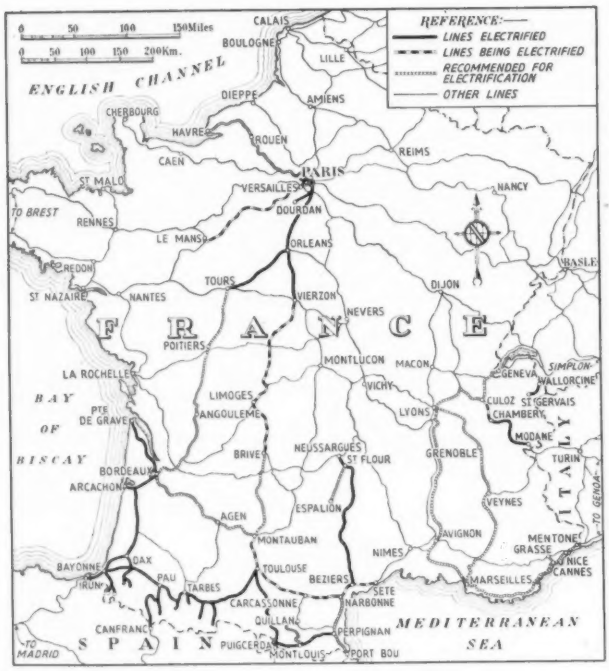
The truck in use at Stepney can be seen in the background in Fig. 2, and in Fig. 3, which show some gear erected for test purposes at Hebburn. The three movements, vertical, transverse and longitudinal, are produced by a small electric motor, and limit switches are provided to prevent over-running, and to centralise the platform before longitudinal movement occurs. The truck cannot be used to lower a single tank or switch, which would plainly be dangerous, and the means for preventing such misuse is shown in Fig. 4. Only when the studs projecting through the platform are all up or all depressed can the platform be moved. If one is depressed, or two, the switch operated by the cable and toggle mechanism must remain open. The diagram on this page shows, on the right-hand unit, the result of an attempt to lower a single tank.

As can be seen very clearly from Fig. 3, there are two sets of 3-phase bus bars. The external connections through cable boxes are most clearly seen in Fig. 1, which shows the installation at Bankside. The rupturing capacity of the units described is 1,500,000 kVA. each, and practically the whole of the erection work for each installation was carried out by means of the truck forming a permanent part of the equipment.

NOTES ON ELECTRIFICATION IN FRANCE

A USEFUL summary of the position of electric traction in France is contained in a recently-issued Department of Overseas Trade Report on Economic Conditions in France which has been compiled by Sir Robert Cahill, Commercial Counsellor to H.M. Embassy, Paris. It appears that the length of electrified lines, which was only 60 route miles in 1914, had increased to 716 route miles in 1928, when the last of these D.O.T. reports was issued. A considerable mileage of steam operated lines was converted in the difficult years following, and by the end of 1932, which concludes the period covered by the report, the electrified route mileage was 1,220, exclusive of secondary and local lines. (At the end of 1933 there were 1,307 route miles converted.) Only the Midi and P.O. and P.L.M. Railways have appreciable lengths of main line electrified, and no active steps have been taken towards the electrification of any part of the Nord or Est systems, although the conversion of the Paris suburban lines of the latter company is mooted. This is due in part to the ease of obtaining coal supplies, to the peculiar vulnerability of an electric system in case of hostilities, and perhaps because the remaining period of the concessions before the reversion of the railways to the State is considered to be too short to permit of the redemption of the capital outlay, which, in the case of the Nord alone, has been estimated at a milliard francs.

The programme of electrification drawn up by the Government in 1920, but suspended in 1924 after partial completion, related to 5,500 miles of route, of which 5,000 miles were then in operation with steam traction. In 1932 a fresh report, based upon the 1920 programme, was issued, and contained suggestions for the electrification of 1,865 route miles over a period of 8-10 years in order to ease the growing unemployment situation and as a stage in the national re-equipment scheme. Further consideration of the question resulted in the conversion of the northern and eastern lines being relegated to some future date, but recommendations were made for the electrification of the following lines, totalling approximately 1,500 route miles, within the next eight years: Paris-Le Havre, 142 miles (Etat); Paris-Le Mans, 131 miles (Etat); Brive-Montauban, 101 miles (P.O.); Tours-Bordeaux,

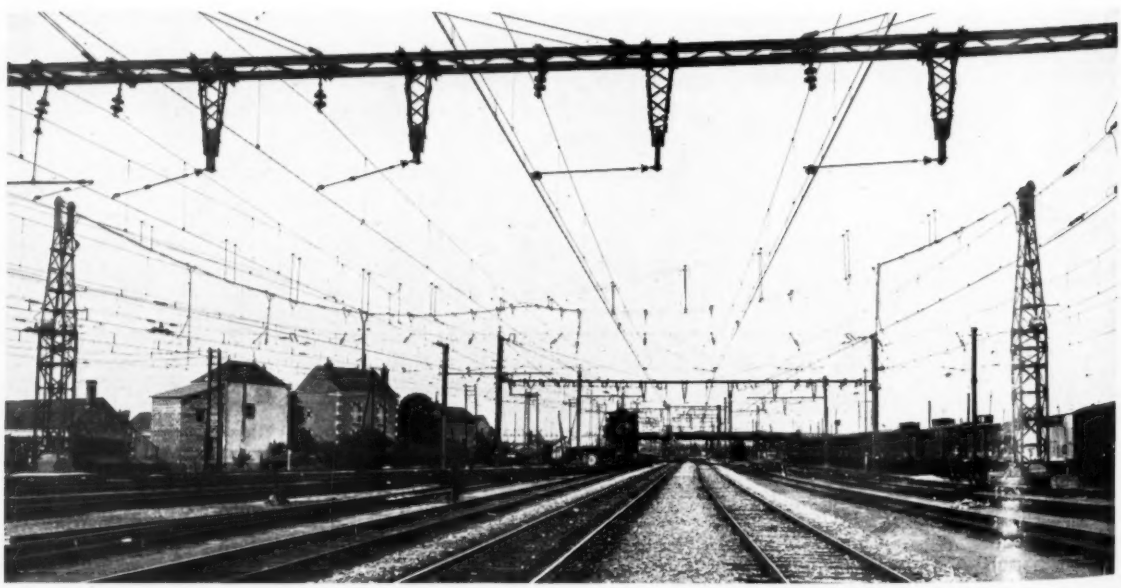


Map of electrified railways in France

214 miles (P.O.); Bordeaux-Montauban, 128 miles (Midi); Narbonne-Port Bou, 66 miles (Midi); and the southern portion of the P.L.M. The companies concerned are now making detailed investigations to decide whether or not the work shall be put in hand, and the Etat has just announced that the conversion of the Paris-Le Mans sections will be undertaken.

As France imports more than one-third of her total coal consumption, the economy in fuel provided by electrification is of some importance. In 1929 the Midi reported a saving of 285,000 tons of coal, a figure which has now probably reached 350,000 tons, by reason of the increased electrified mileage. An annual saving of about 250,000 tons has been recorded by the P.O., and although no figures are available for the P.L.M. and the Etat, which possess 153 route miles of electrified line between them, it is estimated that their combined saving is in the neighbourhood of 200,000 tons, or a total for the country of 800,000 tons, representing a sum of 104 to 152 million fr., according to the price of coal per ton. Current consumption per tonne-km. on the P.O. in 1929 has been given as 11·5 watt-hr. for goods trains, 21 for fast passenger trains, and 27 for suburban trains. (These figures, corresponding to 19, 34·5, and 44 watt-hr. per ton mile, seem remarkably low). Working expenses are stated to be 30 per cent. less than with steam traction.

Approximately 30 to 35 million train-km. per annum are handled electrically in France, at a cost estimated by different authorities as 2·0 to 2·9 fr. less than with steam traction. One railway reported an actual working cost of 2·4 fr. per train-km. About one-third of the total traffic on the Midi, one-fifth that of the P.O., and the greater part of the Paris suburban traffic of the Etat is worked electrically. At the end of 1932 there were 543 electric locomotives and 370 motor coaches in service. Since that time the Midi has acquired six 2-Do-2 express locomotives of 3,950 h.p., and the P.O. has put into service 25 locomotives of the same wheel arrangement. It is estimated that the current consumed yearly by the French railways is 400 million kWh., or only 2·6 per cent. of the total consumption in France. The cost varies, being 27 centimes per kWh. on the Etat and 34 on the P.O. The Paris Metropolitan Railway now operates over a route mileage exceeding 80, and carries between 900 and 1,000 million passengers yearly, and it is claimed that, in proportion to its length, this system has a more intense traffic than the electric railway of any other capital. The Metropolitan operates under a concession from the Municipality of Paris, and receives a fixed sum of 37·85 cents per passenger. The Municipality receives 40 per cent. of the profits.



Typical catenary and cross-catenary forms of overhead construction of 1,500 volt d.c. lines at St. Pierre des Corps on the Paris Orleans Railway

NOTES AND NEWS

Important Siberian Line Completed.—The Soviet Commissariat for Transport recently announced the opening of an important line from Kusnezsk to Novosibirsk on the Trans-Siberian Railway, which will form the principal outlet for the coal mined in the Kuss Basin. According to the provisions of the second Five Year Plan, this 180-mile double-track line is worked electrically on the 3,000 volt d.c. system.

The standard type of single-phase electric locomotive for passenger and goods traffic on the Rhaetian Railway

Swedish Extension.—It is reported that a beginning has been made with the electrification of the 126-mile line of the Swedish State Railways from Laxaa on the Stockholm-Gothenburg line to Charlottenberg on the Norwegian frontier. The work will take over two years. It is expected that by the end of 1935 the whole of the west coast line from Gothenburg to Malmo will be operated electrically on the standard single-phase 15,000 volts system.

The Cost Factor in Roller Bearings.—In the article which appeared in our last issue under the above title the statement that, of more than 100 coaches in service on the Metropolitan line of the London Passenger Transport Board, 97 had Timken bearings appears to have misled some of our readers, who have pointed out to us that there are on the Metropolitan 14 coaches fitted with S.K.F. roller bearings and 7 with Ransome & Marles bearings.

Hungarian Electrification Allowance.—A sum of 2,750,000 pengos, (approximately £160,000 at the present rate of exchange), has been allotted in the 1934-35 budget of the Hungarian State Railways for the completion of the conversion work on the Komarom-Hegyeshalom line, 53 miles long, which forms the last Hungarian section of the main route between Vienna and Budapest. Single-phase current at 15,000 volts 50 cycles is to be used, and the line will form a prolongation of the Budapest-Komarom section, which was opened to electric working in September, 1932.

P.O. Electrification Figures.—As a result of the conversion of the Orleans-Tours section, opened to electric traction in July of last year, the consumption of energy during 1933 increased to 139 million kWh measured at the ingoing busbars of the sub-stations. Due to the small rainfall the output of the hydro-electric stations at Eguzon and Coindre was 62 and 75 million kWh respectively, compared with 96 and 105 millions in 1932. The electrically-hauled traffic amounted to 6,440,000 train-miles and 3,350,000,000 trailing ton-miles.

Russian Electrification Activities.—A final survey is now being made of the route to be followed by the new electric railway between Kartali and Akmolinsk, in Siberia. This 390-mile line will unite the Karagandinsk basin with the Magnitogorsk metallurgical works and other industrial enterprises in the Urals. The Kartali-Akmolinsk line will eventually form part of the South Siberian railway, running from Kartali to Semiplatinsk on the Turksib railway as shown in the map reproduced in the issue of this Supplement for December 15 last. Electrification work is now being pushed forward on the Kandalaksha-Apatite-Khibin section of the Murmansk railway and an expenditure for this year of 3,500,000 roubles has been assigned to the conversion of this 70-mile division.

Paris Suburban Lines.—Electrification of the line from the Luxembourg terminus to Massy-Palaiseau, 10½ miles, and the branch from Bourg-la-Reine to Sceaux, 2 miles, is now in progress. On completion at the end of next year, these lines will be taken over from the Paris-Orleans Railway by the Paris Metropolitan. Plans for altering the station at Massy-Palaiseau so as to enable the electric trains to reverse there have not yet been approved, as the question of extending the electrification on to Limours, 38 miles from Paris, is under consideration.

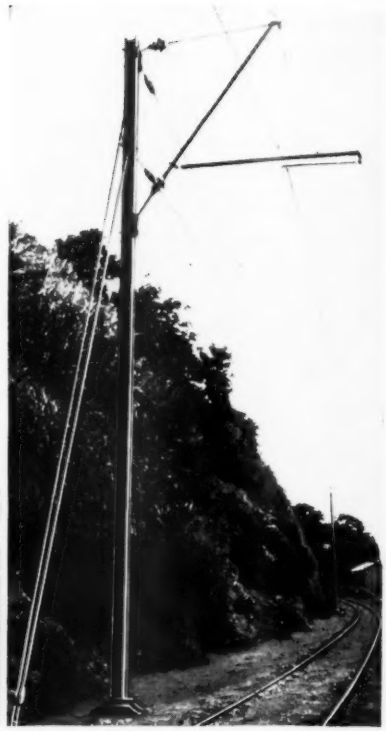
Electric Locomotive Performance.—The single-phase electric locomotives of the metre gauge Rhaetian Railway, in Switzerland, cover an average annual mileage of 40,000 miles over heavy grades and sharp curves, the maximum mileage per locomotive being about 50,000 miles. Taken over a period of two years an average of 83 per cent. of the stud of 30 locomotives is in service at a time, 3·5 per cent. are undergoing light repairs, 6·5 per cent. are being given heavy repairs, and 7 per cent. are in reserve. The cost of maintenance and repairs of the 15 latest locomotives averages 19·7 Sw. cents per km.

French Main Line Conversion.—The conversion of the Etat main line from Paris to Le Mans, briefly announced in the issue of this Supplement for July 27, is to be spread over a period of four years, and, together with the probable conversion of certain Paris suburban lines of the Est, will cost approximately 820 million fr., of which 250 million fr. will be spent in each of the first three years and 70 millions in the fourth year. The two schemes will give employment to 16,000 workers over an average period of 30 months, and the electrical industry will benefit by orders to the extent of 285 million fr., the copper industry to 126 millions, other metallurgical industries to 220 millions, and constructional steelworks to 46 millions.

Turkish Electric Railways.—It is reported that the construction of a new electric railway between Zougouldak and Heraclea will soon begin. It will eventually form part of the proposed Silijos-Heraclea line, and will link up the coal basins of the district. Studies are also being made of the conversion of the heavily-graded Biledchik-Bosujuk section on the Anatolian Railway main line, the power for which would be supplied by two hydro-electric stations on the rivers Sakaria and Karasu.

ELECTRIFICATION OF THE COSTA RICA STATE RAILWAY

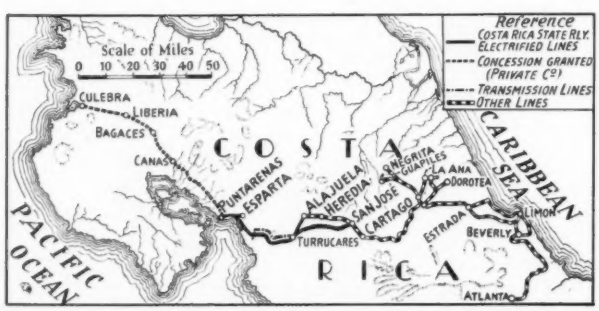
Single-phase operation was adopted for the first time in the tropics when this 80-mile line through difficult country was converted



Above : Double-bogie single-phase electric locomotive of 800 h.p. on the State-owned Pacific Railway
Right : Contact line mast at curve, showing pull-off device and catenary anchoring

THE State Railway of Costa Rica connects the capital, San José, lying at an altitude of 1,165 m. (3,830 ft.) with the port of Puntarenas, on the coast of the Pacific Ocean, 130 km. (81 miles) distant. Close to the coast a branch line runs off towards Esparta, and from the junction the main line traverses a swampy area and then climbs through a mountainous district. Curves with a radius as small as 46 m. (150 ft.) and gradients up to 2·5 per cent. (1 in 40) have to be negotiated. From Turrucares a branch goes off to Alaguela, as indicated on the accompanying map.

Some years ago steam operation proved unable to cope with the increasing traffic, and so a decision was made to adapt the railway to prevailing conditions by electrifying it. The river Poas provided the source of primary power for generating the requisite energy, and a hydro-electric station for the exclusive use of the railway was erected on this river close to Turrucares. The electrification of the line, the modifications to the railway stations, the design and construction of the power station, and the electric



Map of railways in Costa Rica showing electrified line

locomotives were entrusted to the A.E.G. of Berlin, and the conversion was completed in 1929. As there was no suitable raw or finished material in Costa Rica, all the necessary machines, apparatus and tools had to be shipped from Germany, and this involved a sum of roughly 250,000 RM.

Great difficulties were experienced in erecting the electrical plant in the swampy, thickly wooded, and mountainous districts, particularly in the case of the power station, which is situated in a jungle. The narrow river bed and the lack of roads made the transport of the building materials difficult. The upper canal demanded extensive damming operations, and unusually deep foundations had to be made for the weir dam. There were no plans available for the position of the railway track and curves, which added to the difficulties of the trolley and booster line erection. Photographed curve sheets were used as a basis for pegging out the poles.

As there is an adequate supply of water power, there was no need to conserve current by regeneration. The adoption of single-phase current at the high tension of 15 kV., 20 cycles, rendered it possible to feed the entire line without a substation. This system of supply, although used extensively in Europe, was applied to a railway in a tropical country for the first time in Costa Rica.

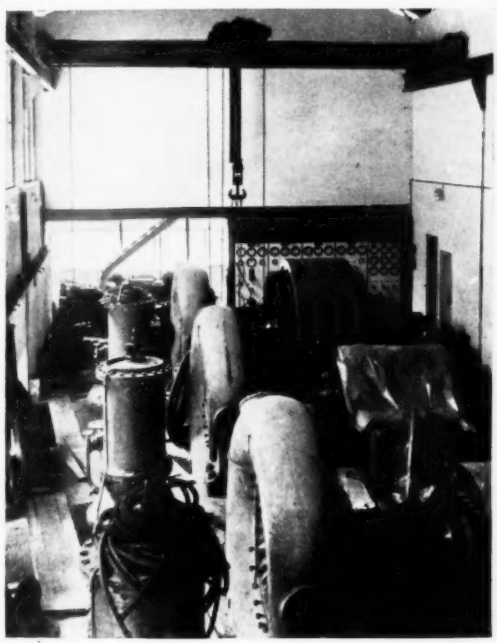
Power Supply

The power station was erected in the narrow river bed of the Poas. According to the season of the year, the quantity of water flowing in the river fluctuates between 5 and 200 cu. m. per sec. (177 and 7,080 cu. ft. per sec.), which is a very considerable variation. Consequently, the 4·0 km. (2·5 miles) upper canal (head race) had to be protected by extensive cofferdams. At the end of this canal is the weir. Running beside the delivery pipe line

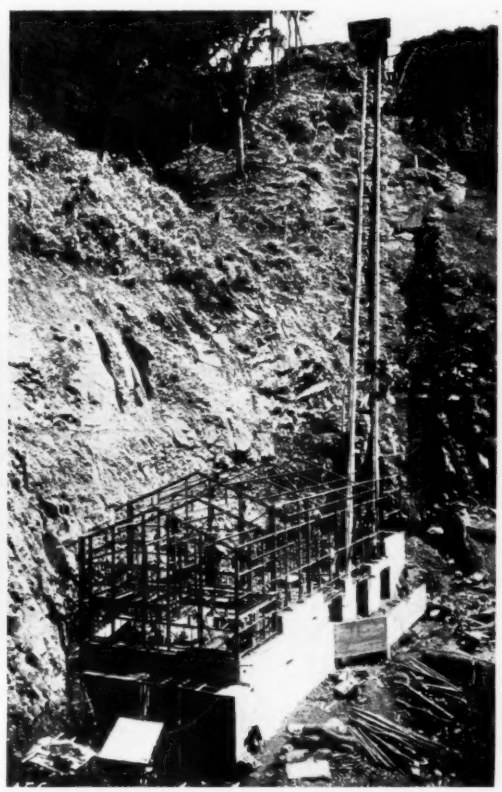
is an incline, which was used during the building operations for transporting the building materials, but now used for inspecting the pipe line. The transformer station is situated 70 m. (230 ft.) above the power station. The feeder line crossing the river is 250 m. (820 ft.) long, and its anchoring tower near the station also serves as a crane for lifting out the transformer cores. There are three generating sets installed in the station. Each comprises a vertical Francis spiral water turbine of 2,700 h.p. output, driving a single-phase alternator with a terminal voltage of 6,000, which is stepped up to 16,600 volts in the transformer station.

An overhead line about 5 km. (3·1 miles) long runs from the latter station to a switching plant at Turrucares station. The lines radiating to the feeding points are strung on the overhead trolley wire poles. Each of the three overhead feeder lines has a copper cross-section of 70 sq. mm. (0·108 sq. in.), and is carried on solid core pin-type insulators. The insulators are mounted on V-shaped brackets in order to obtain a good bird protection. A fourth line of the same cross-section acts as return circuit. At Turrucares, the last-named is connected to the rails, which are utilised for the return circuit. To this end, all the rails are bonded, and the return circuit is earthed at two points. At the terminal railway stations, at Coyolar, and in the transformer station, there is Bendman lightning equipment covering the protection of all the lines.

The suspension cable of the catenary trolley wires is made of bronze with a cross-section of 35 sq. mm. (0·05 sq. in.), and the oval trolley wire is made from hard copper of 80 sq. mm. (0·122 sq. in.) cross-section. The useful width of the collector bow is 1,500 mm. (4 ft. 11 in.). The trolley line is calculated for temperatures varying from zero to 60 deg. C., and the line is adjustable by hand. On the straight, and on curves of a flatter radius than 1,560 m. (5,000 ft.), the span between poles is 75 m. (245 ft.), and for curves with a radius down to 375 m. (1,230 ft.) the span is 50 m. (164 ft.). At smaller radii, one to three intermediate poles are mounted between the main poles. Trolley wire supporting poles which also carry the feeder lines are 400 mm. (15·7 in.) higher than the normal, so that in curves the feeder line can cut across the trolley wire. During the cold and hot seasons, the trolley wires are manually adjusted for a tension of 7-11 kg. per sq. mm. and 6-10 kg. per sq. mm. respectively; the wind forces on the wires are calculated at a tensile stress of 8 kg. per sq. mm. At the stations the catenary system is suspended on cross-span and insulated aligning wires by means of rod insulators, similar to the method employed by the German State Railway.



Above: Interior of power station during erection. The water turbines are down the centre

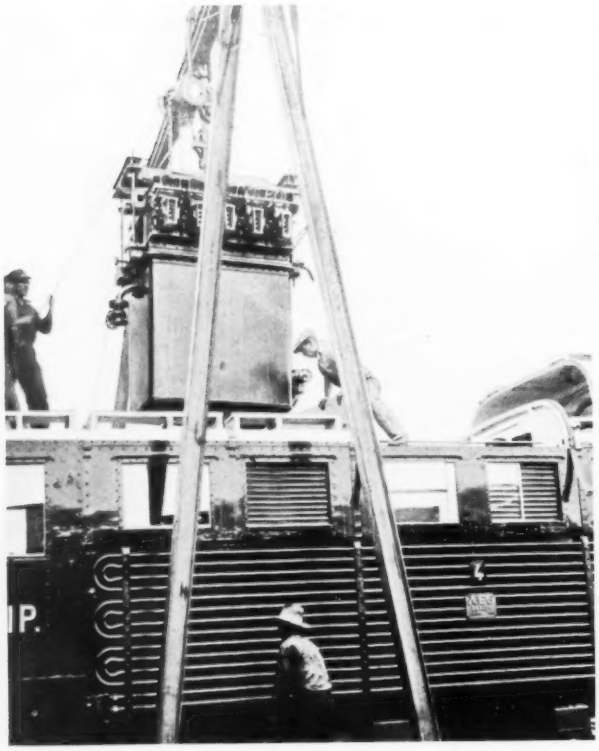


Right: Erection of hydro-electric power station in valley of the River Poas

A solid-core pin type insulator with a petticoat of 220 mm. (8·7 in.) diameter, 180 mm. (7·1 in.) overall height and a neck 50 mm. (1·96 in.) long is used for practically all purposes; at the top it has a neck for taking the loop of the pull-off wires as well as a longitudinal groove for receiving the feeder wires. The rod insulators were given a dry test at 78 and 92 kV. and a wet test at 62-63 kV. They stand up to a lateral pull of 1,800 kg. (3,975 lb.). The trolley wires are strung on pivoted brackets on the poles. Solid core insulators are also used on the horn type switches, which are rated for a continuous current carrying capacity of 500 amp. Line isolators of the A.E.G. type, complete with rod insulator and arcing horns, are used for sectionalising the line.

Locomotives

The A.E.G. locomotive works at Berlin-Hennigsdorf supplied eight AIA + AIA electric locomotives for hauling

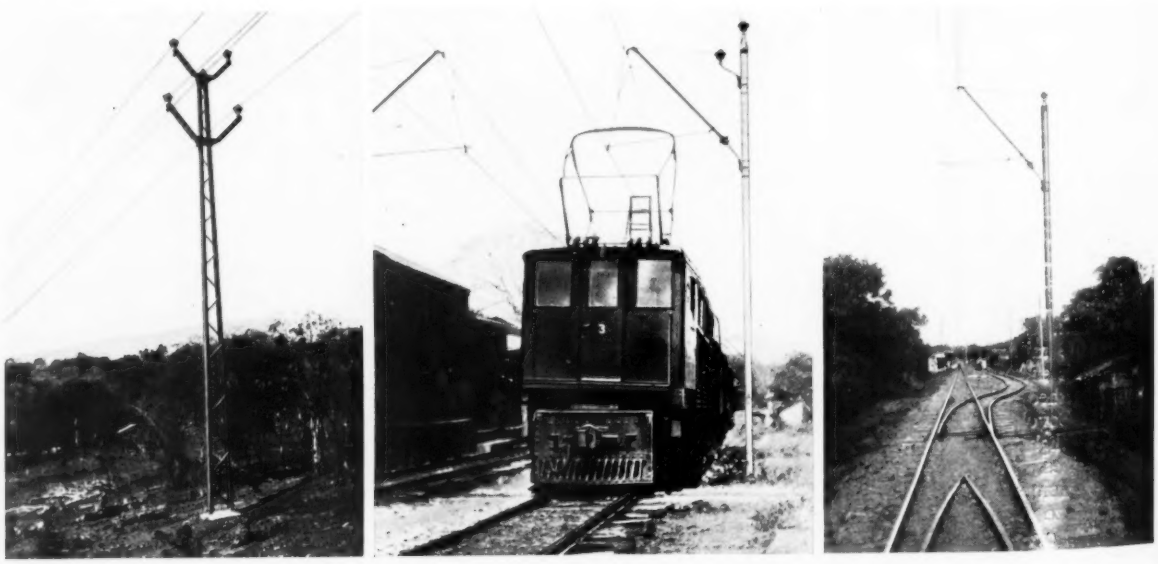


Lowering an oil-cooled static transformer into one of the Costa Rica locomotives

passenger and freight trains up to 200 tons in weight. This wheel arrangement was selected in order to obtain the best distribution of the weight on the rails, as the maximum axle load is limited to 11·5 tonnes. The tyres of the carrying wheels are 160 mm. (6·3 in.) wide, but have no flanges, so that sharp curves can be easily negotiated. The service weight of the locomotive is 56·8 tonnes, the adhesive weight 46 tonnes, the diameter of the driving wheels 1,250 mm. (49·5 in.) and that of the running wheels 700 mm. (27·5 in.). Leading running wheels were not essential on account of the comparatively low maximum speed of 50 km.p.h. (31 m.p.h.) on the level. The distance between the bogie centres is 5,400 mm. (17 ft. 8 in.), the overall wheel base 8,300 mm. (27 ft. 2 in.), and the fixed wheelbase in the bogie truck 2,900 mm. (9 ft. 6 in.). The draw gear is of the Sharon automatic type, and with the cowcatchers is mounted on the front of the bogie trucks. The overall length of the locomotive is 12,100 mm. (39 ft. 7 in.). In addition to the pivot pins of the bogie trucks, the locomotive body is carried by spring-supported side bearers.

The body structure extends over the entire length of the locomotive, and consists of an underframe of girder sections to which the body is riveted. The driver's cabs at each end are entered through end doors from a narrow platform, and are connected together by two side gangways running through the intervening equipment compartment. Cooling air enters this compartment through louvres in the top part of the side walls, and the ingress of dust and moisture is prevented by filtering material stretched across. Parts of the roof above the middle of the equipment room can be easily detached, and the installation or removal of the transformers and other parts of the electrical equipment can be effected through this aperture with the aid of a crane. The maximum height of the roof over the rail head is 3,750 mm. (12 ft. 3 in.), and the maximum width of the locomotive 2,600 mm. (8 ft. 6½ in.). The Westinghouse air brake operates blocks on all driving wheels and works in conjunction with a hand brake which controls the blocks on the adjacent bogie only. The compressed air operated sander only sands the front driving wheels in the respective direction of running. The compressed air for the brakes, sanding, raising the pantograph, and for the electric control is produced by a two-stage A.E.G. compressor.

The current from the trolley wire passes through two pantographs (of the German State Railway standard pattern), and an oil circuit-breaker to a static transformer.



Left : 16 kV. overhead transmission line with bird protection
Centre : One of the eight electric locomotives on a mixed train
Right : Overhead contact line supported by mast with swinging bracket

which steps down the trolley wire voltage to the normal operating voltage of the motors. The transformer has a vertical core which is inserted in an oil-filled plain steel tank. The high temperature in the tropics demanded an oil expansion vessel, which is mounted on the transformer tank. The oil for cooling the transformer is circulated by a pump through coils secured to the outside of the equipment compartment walls, and is cooled by the natural draught of movement. On the cover of the transformer are 10 electro-magnetic step contactors for regulating the speed of the traction motors, and these contactors are controlled from the two master controllers.

The motors are of the nose-suspended type, with single gears having a ratio of 6·06 to 1. Each motor has a continuous rating of 120 kW. and an hourly rating of 150 kW., corresponding to a total continuous locomotive output at the motor shafts of 645 h.p. at 25 km.p.h. (15·5 m.p.h.) or an hourly output of 810 h.p. The motors develop a tractive effort at the wheel rims of 7,000 kg. (15,400 lb.) continuously and 8,800 kg. (19,600 lb.) hourly ; the maximum starting tractive effort of the locomotive which can be maintained for 10 sec. amounts to 13,000 kg. (28,700 lb.), corresponding to an adhesion factor of 3·54. The traction motors are force-ventilated, and each pair of motors has a fan driven by a 3·7 kW. motor. In the machine compartment there are two small apparatus frames carrying the isolating contactors, motor fuses, isolators, fuses and contactors for the auxiliary circuits, and the electro-pneumatic reversing gear for the four motors. All auxiliary circuits are operated at 200 volts, obtained from a tapping of the oil transformers, but the 24 volt potential for the lighting and signal circuits of the locomotive is supplied by a small transformer accommodated in the oil tank of the main transformer. Apart from the master controllers, the drivers' cabs are equipped with brake valve, sander valve, pantograph valve, vertical handwheel for brakes, speed indicators, brake pressure gauges, contact line voltmeter, motor ammeters, &c.

MERCURY ARC RECTIFIERS

IV

The operation of steel tank rectifiers and special applications of grid control in traction service

THE d.c. voltage delivered by a mercury arc rectifier contains certain ripples or harmonics superimposed on its mean value. The amplitude of the ripples is determined mainly by the transformer reactance and their frequencies are generally multiples of the a.c. supply frequency and the number of rectifier phases. Tests on an English Electric 6-phase rectifier, running on 50-cycle supply and no load, show the r.m.s. values of the 300, 600, 900 and 1,200-cycle ripples to be respectively about 4·0, 1·0, 0·5 and 0·25 per cent. of the d.c. voltage, the amplitude of the higher frequencies being negligible. A simple cathode choke or smoothing reactor connected in the d.c. lead from the cathode has a very substantial smoothing effect when the rectifier is on load and operating at full d.c. voltage, the choke being magnetised by the d.c. load and offering great impedance to the high-frequency ripples.

If the d.c. voltage is reduced by grid control, the amplitude of the ripples is increased and some of those which were unimportant at full voltage may now cause interference in telephone or other communication circuits. For example, with the d.c. voltage reduced to 80 per cent. of the normal by grid control, the r.m.s. value of the 300-cycle (6 × 50) harmonic is increased from 4 to 14 per cent. of the d.c. volts, and the higher harmonics are increased in similar proportion. As the d.c. load decreases, the smoothing effect of the cathode choke becomes less, and the only way to prevent the ripples travelling along the d.c. circuit is to by-pass them through shunt circuits, each consisting of a reactor and condenser tuned for resonance at the frequency of a particular ripple. A separate tuned shunt is required for each of the frequencies which would otherwise cause trouble. Two or four of these shunts, for frequencies of 300 and 600 cycles or up to 1,200 cycles, as the case may be, generally suffice for a rectifier without grid control. In the case of grid-controlled rectifiers, four resonant shunts generally suffice if not more than 10 per cent. voltage compounding is provided, but extra shunts may be necessary where a wider range of voltage control is practised.

The ripples in the d.c. output are never sufficient to disturb the satisfactory operation of traction motors. In some instances there is no possibility of their affecting communication circuits, and in other cases a rearrangement of circuits may be simpler and cheaper than the provision of tuned shunts.

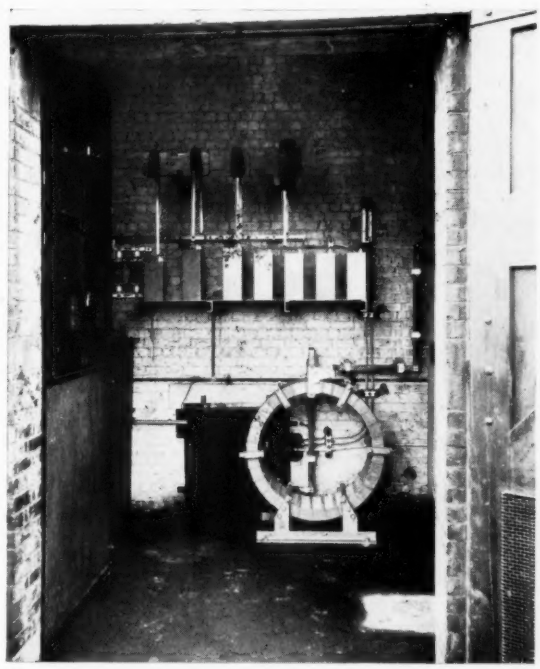


Fig. 1.—Smoothing circuit equipment comprising air-core choke and tuned resonant shunts

The accompanying illustration, Fig. 1, shows the smoothing circuit equipment for one of the B.T.H. steel-tank rectifier units as used in the Erimus substation of the Newport-Shildon mineral line of the L.N.E.R. For each rectifier unit there is a d.c. air-core self-cooled reactor in the main negative connection to the transformer neutral and a series of resonant shunts and condensers tuned to the frequencies of the principal harmonics in the d.c. voltage and connected across the d.c. system.

Control and Protection

It is not always understood how the rectifier arc is transferred automatically from anode to anode during

normal operation when a special ignition electrode is required to produce the arc in the first instance. On starting up, the withdrawal of the ignition electrode from the cathode breaks metallic contact at the surface of the mercury and, in so doing, strikes an arc and forms a cathode hot-spot which emits electrons. Once electrons are emitted, they are attracted by any one of the anodes which is at a sufficient positive potential (say 15 to 25 volts) with regard to the cathode, and the passage of the electrons from the cathode to the anode constitutes a current flow, which is conventionally said to flow from the anode to the cathode, the electrons being particles of negative electricity. As soon as the potential of one anode becomes inadequate the arc (or electron stream) transfers to any other anode which is at an appropriate potential. So far from any special means being required to effect this transference, special measures—in the shape of negatively-charged grids—are required to prevent it, provided that the anode is sufficiently positive relative to the cathode.

A small inverse current sometimes flows from cathode to anode after the completion of the burning period of the anode. If this inverse current be too great, it may develop into a backfire with complete loss of rectifying action. The cause of the inverse current lies in the formation of a positive space charge, *i.e.*, a cloud of positive ions near the anode during its period of burning. After that period is over, the anode becomes negatively charged and then attracts the positive ions, the flow of which constitutes the inverse current. A deionising grid mounted in the anode shield near the anode automatically acquires a negative potential during the burning period, at the close of which it attracts and neutralises the positive ions.

Backfire and Overload Protection

Backfires are of rare occurrence in modern rectifiers, but provision must be made for interrupting them. A high-speed circuit breaker may be provided in the d.c. circuit, with the further protection of high-speed circuit breakers on the a.c. side, or all the anodes may be blocked by maintaining a suitable negative potential on their control grids. This amounts to using the rectifier itself as a circuit breaker, a function for which it is well suited because there are no contacts or other parts to be damaged by burning. The only effect of the energy dissipated in interrupting the current is to evaporate more mercury, which is promptly condensed by the cooling system and returned to the cathode.

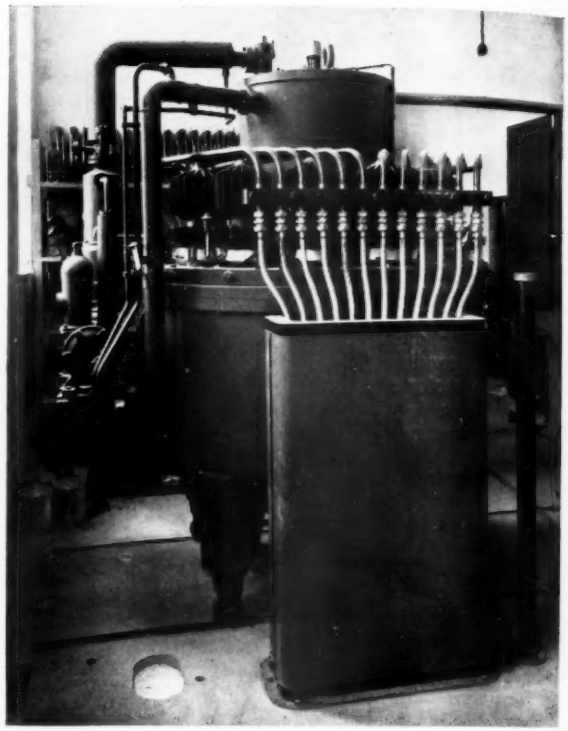


Fig. 3—One of the nine Brown-Boveri steel tank rectifiers in the Copenhagen suburban system

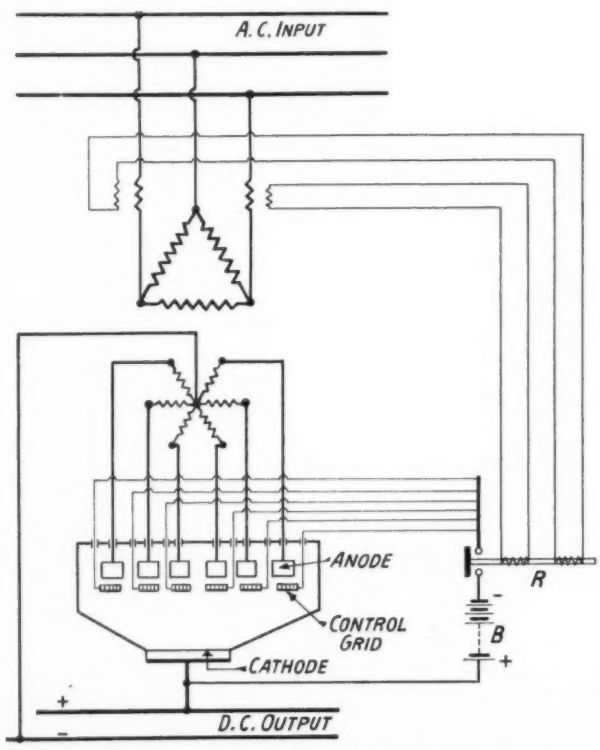


Fig. 2—Interruption of overload or backfire by simultaneous negative excitation of all grids

The principle of current interruption by grid excitation is illustrated by Fig. 2, showing an arrangement used by the English Electric Co. to deal with backfire or overload. The grids are all charged negatively by the battery *B* when the high-speed overload relay *R* closes. This relay may be energised from either the a.c. or the d.c. systems and it closes when either the current or the rate of change of current, as the case may be, exceeds a predetermined value.

It must be clearly understood that the grids cannot extinguish the arc at the anode on which it is burning at the moment of the overload, but they prevent its being transferred to any other anode. In other words the overload or backfire cannot endure for longer, at the most, than the full burning time of one anode. In the course of tests on a rectifier fitted with this form of protection, the rectifier was delivering 2,340 amp. at 795 volts when a short-circuit was applied; the current rose to 23,200 amp. in about 0·01 sec. and the arc was extinguished in 0·02 sec. by the application of 150 volts (negative) to the grids.

For traction systems this form of protection can be arranged to operate only on backfire or very high overload, so that a track fault cleared by the circuit breaker of the feeder concerned does not shut down the rectifier.

If desired, the relay can be made self-setting so that power is restored to the d.c. bus-bars, with only 0·1-0·25 sec. interruption, say three times in succession and then cut off if the fault still persists.

Manual and Automatic Control

A mercury rectifier installation can be operated very simply by manual control, but as the equipment is frequently in a more or less remote substation and needs a minimum of supervision and maintenance, it is becoming increasingly common to provide either remote (supervisory) control or fully automatic control.

Where manual control is employed, the operations are generally limited to switching on excitation and ignition and closing the main e.h.t. switch, the rectifier circuit-breaker then connecting automatically to the d.c. bars. The protective features may then comprise a.c. overload and earth leakage relays on the h.t. side, a reverse-current high-speed breaker between the cathode and the d.c. bus-bars (or grid fault-clearing may be arranged), protective thermostats on the rectifier, and fuses or overload relays in the auxiliary circuits.

The details of automatic control systems vary considerably, but the main contingencies to be guarded against are overload, failure of a.c. supply, failure of supply to auxiliaries, low (soft) vacuum, low water pressure, overheating of rectifier, failure to start, and backfire. A full equipment of signalling and alarm devices, and transmitting measuring instruments must be provided. The same features are required for remote control as for automatic operation, but those requiring regulation are controlled through pilot wires from a central board instead of automatically in the substation.

The 2,500 kW., 1,650 volts steel-tank rectifier illustrated in Fig. 3 is one of nine installed in four substations of the Copenhagen suburban electrification,* the automatic equipment in each substation being supervised from the main control room at Enghave.

Rating, Efficiency and Power Factor

The general information already given concerning the rating and performance of steel-tank rectifiers may be supplemented by data relating to particular installations.† The efficiencies of a General Electric 2,000 amp., 630 volts rectifier and rotary converter, both designed to the same specification, compare as follows:—

Load.	5/4	1/1	¾	½	¼
Rectifier ..	93·0	94·0	94·6	94·5	93·5
Rotary converter	94·0	94·0	93·6	92·4	87·5

The B.T.H. rectifiers in the substations of the Cockfosters extension of the London Underground are each rated at 1,500 kW. (630 volts, 2,400 amp.) continuously with 50 per cent. overload capacity for one hour, and 200 per cent. overload capacity for short periods. The guaranteed efficiencies (easily met on test) are: 93·37 per cent. on full load and 93·34 per cent. on half-load, allowing for all auxiliaries, smoothing circuit, and stray losses.

The Bruce Peebles 2,500 kW. (660 volts, 3,790 amp.) rectifiers for the London-Brighton-Worthing section of the Southern Railway, one of which is illustrated in Fig. 4, are capable of carrying 20 per cent. overload for 15 min., 60 per cent. for 5 min., 140 per cent. for ½ min., and 220 per cent. momentarily. The overall efficiencies on acceptance test, including all auxiliaries, were: 95·0 per cent. at full-load, 96·0 per cent. at 2,000 kW. (80 per cent. load), and 96·9 per cent. at 1,000 kW. (40 per cent. load).

Two Brown Boveri rectifiers in the Bône substation of the Bône-Oued-Kébérit section of the Algerian State Railway, each rated at 2,000 kW., 3,000 volts d.c., have an efficiency (rectifier alone) exceeding 99 per cent. at loads up to 1,000 amp., the overall efficiency of transformer and rectifier being 96·8 per cent. from 1½-load to full-load, 96·5 per cent. at ¾-load, 95·8 per cent. at ½-load, and 93·2 per cent. at ¼-load.

The power factor on the a.c. side of a mercury rectifier is affected by: (1) the displacement of the current wave, due to transformer reactance and the point of ignition of the arc; and (2) the distortion of the current wave, which depends on the number of phases and arrangement of the secondary windings. The lower-than-unity power factor resulting from these causes is a matter of dissimilarity of wave form and position without, however, any appreciable component of current in quadrature with the voltage, *i.e.*, no important amount of demagnetising current is taken from the a.c. mains, even when the power factor is as low as 0·6 due to the d.c. voltage being reduced to 60 per cent. of normal by grid control. Such a degree of voltage reduction is not ordinarily required in traction service. For practical purposes, it may be taken that the power factor of a rectifier on full load is about 0·93-0·96. On inverted operation (d.c. to a.c.) the power factor is 0·82-0·88.

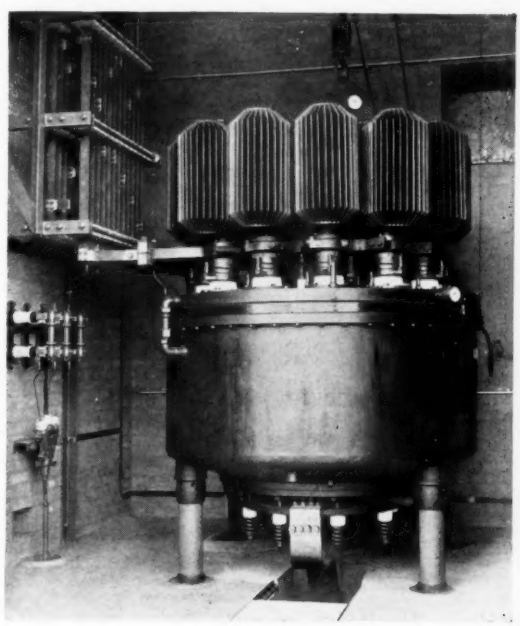


Fig. 4—One of the Bruce Peebles 2,500 kW. steel tank rectifiers in Gatwick substation, Southern Railway

Inverted Operation

The versatility of the grid-controlled rectifier is due primarily to the fact that grid-control, operating on the blocking principle and with a very small consumption of energy, enables the arc to be taken over by an anode at any desired point in the a.c. cycle or not at all, as the case may be. The applications of this principle to voltage control and to the interruption of overload or backfire have already been explained.

* See *Electric Railway Traction Supplement*, October 27, 1933, page 627.

† As circumstances differ, the figures cited must not be taken as indicative of the relative merits of the various installations. Differences in overload capacity denote different bases of rating rather than any inherent difference between rectifiers.

Another important possibility of grid control is that of inverted operation of the rectifier, or the regeneration of a.c. from d.c. For this, the d.c. busbar volts must be higher than the average d.c. voltage of the rectifier, and the grid control must be arranged to ignite the arc during the reverse polarity of the anodes. The rectifier current must, however, flow from the anode to the cathode, a condition that is fulfilled by reversing the d.c. connections, the positive being now connected to the transformer neutral and the negative to the cathode. All the grids are negative with respect to the anodes except at the moments when one grid (each in turn) is given a positive bias to fire the corresponding anode. The anodes are fired during their negative half cycles of voltage, and the arc is extinguished when the a.c. voltage wave becomes more negative than the cathode; the arc can burn only while the anode is positive to the cathode and when this ceases to be so the arc is transferred to the next anode by grid control.

The current flowing through each anode in turn, and therefore in the corresponding phases of the transformer, induce alternating current in the primary (now actually the secondary) of the transformer and feed power to the a.c. mains. This action has been effected experimentally to the extent of many thousands of kW., and there can be no doubt that regeneration by the inverted operation of mercury rectifiers will become of considerable importance in traction service. Its practicability depends essentially on grid-control to determine the sequence and timing of the arc on the various anodes. As the regenerated voltage of a motor decreases with speed it can be followed by altering the grid control, thus maintaining steady current down to zero volts (standstill). The regenerated power must be fed to an a.c. system kept live from another source, which supplies magnetising current to the transformer and maintains the alternating voltage needed for the commutation of the arc.

A further application of grid control which may be

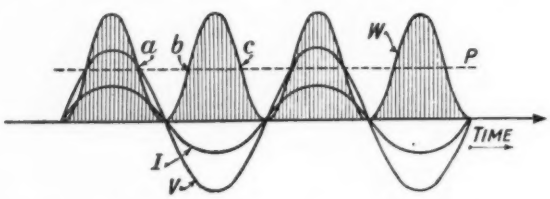


Fig. 5.—Diagram illustrating the pulsation of single-phase power

mentioned but cannot here be fully discussed is that of operating a series-type single-phase motor without a commutator, meanwhile retaining full control of starting and speed.

Phase and Frequency Conversion

From the standpoint of economy in generation and distribution it may sometimes be very advantageous to take energy for electric traction from the general electricity supply network or networks of the districts traversed by the railway. Without discussing the economics of the question, which must be considered for each case on its merits, it may be pointed out that the mercury rectifier offers an attractive means of supplying a low-frequency single-phase traction system from a standard 3-phase, 50-cycle industrial or general network, with the possibility of regenerative return of energy from the traction system if required.

As applied to such service, the mercury rectifier is better described as a mercury converter though the construction of the apparatus remains the same. A fundamental difficulty in the conversion of three-phase to single-phase energy is that the total power delivered by the three phases of a 3-phase system is constant, represented say by the horizontal line *P*, Fig. 5, whereas a single-phase voltage *V* and current *I* produce a pulsating power curve *W*, and although the average of this curve be the line *P* as before, it is evident that the single-phase output is alternately less and greater than the mean effective value. If the 3-phase system is to be loaded symmetrically, some means must be found for storing the excess of three-phase power available during such periods as *ab* and releasing it during the following half-cycle *bc*. No rotating mass or storage battery is available for this purpose and

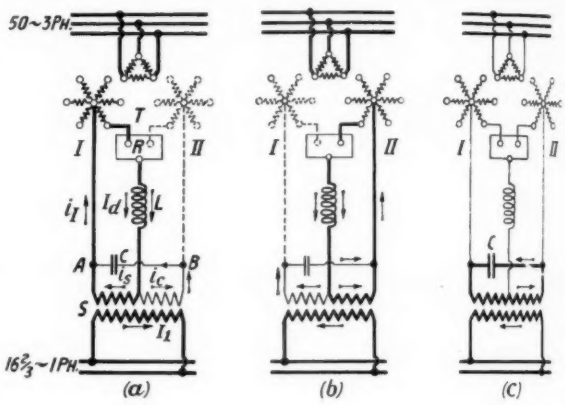


Fig. 6.—Diagrammatic representation of circuits and current flow in Brown Boveri static converter

it is obviously undesirable that it should be provided, for this would destroy the simplicity and/or static nature of the equipment. The solution devised by Brown Boveri is based on the use of a resonant combination of choke coils and condensers in which the requisite amount of energy can be kept oscillating with very little loss. The condensers are also able to supply the full wattless power to the single-phase network.

The arrangement employed is shown diagrammatically in Fig. 6, only the essential features being represented.* A three-phase transformer *T* feeds the secondary systems *I*, *II* which operate alternately to supply the alternate half-cycles of single-phase current through the single-phase transformer *S* as indicated by the heavy lines in Figs. 6 (*a*), (*b*). The heavy lines in Fig. 6 (*c*) represent the condenser *C* supplying wattless power to the single-phase network as further explained below. The important functions of voltage-smoothing and current-smoothing are performed respectively by the choking coil *L* and condenser *C*, the choke *L* being connected in the cathode lead of the rectifier *R* and the condenser *C* being shunted across the primary of the single-phase transformer *S*.

In Fig. 6 (*a*), corresponding to the first half-wave at $16\frac{2}{3}$ cycles, the anodes of system *I* are burning, system *II* being meanwhile blocked by grid control (not shown in the diagram). In Fig. 6 (*b*), corresponding to the second half-wave at $16\frac{2}{3}$ cycles, system *II* burns and system *I* is blocked. The conditions operating during the complete cycle may be explained by reference to Fig. 7, in which E_a represents the 3-phase, 50-cycle voltage and E_1 single-phase, $16\frac{2}{3}$-cycles voltage,† both being sinusoidal.

* For a complete treatment of the theory and operation of this converter, see *Brown Boveri Review*, June, 1934.

† The wave-form is the same for the primary and secondary voltages of the single-phase transformer, and, to simplify the explanation, it is assumed that this transformer has a 1:1 ratio, so that the primary and secondary voltages are equal.

Voltage.—During the first half-cycle of the $16\frac{2}{3}$-cycle supply, there is a constant d.c. voltage e_1 between the rectifier cathode and the neutral of the system I as shown by the shaded area of the e_1 curve, Fig. 7. The difference between the constant voltage e_1 and the single-phase voltage E_1 is accounted for by the choke or voltage smoother L, the voltage across which is as shown at e_L. Adding the ordinates of the shaded areas in E_1 and e^L, we obtain those of e_1. During the next half-cycle, *II* burns and *I* is blocked; the voltage e_1 is no longer provided by the rectifier but the voltage across L is the same as before (now derived from *II*) and there is a negative half-wave of voltage E_1 (also derived from *II*), hence the voltage e_1 now follows the negative curve *n*. Meanwhile there is a constant d.c. voltage e_{II} (not shown) between the cathode and the neutral of *II*.

Current.—The direct current I_d flowing from the cathode of the rectifier is constant, but flows alternately through systems *I* and *II* so that, during the positive half-waves of single-phase current I_1, the current in system *I* is represented by the rectangles i_1. The difference between the rectangular current i_1 and the sinusoidal current I_1 is accounted for by the condenser or current smoother C. It will be seen from Fig. 6(*a*), that the current I_d divides,

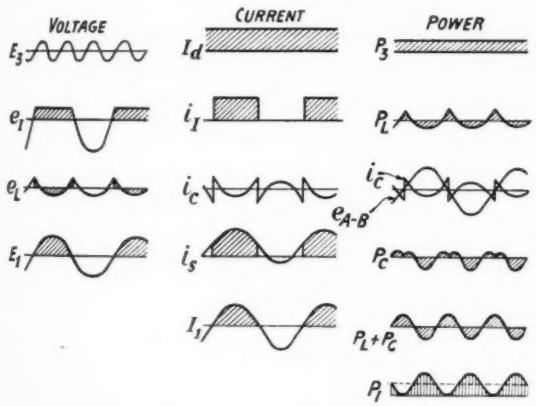


Fig. 7—Diagram illustrating action of voltage and current smoother in producing sinusoidal single-phase output.

a part flowing through the right-hand half of the primary of S and the condenser C to A, where it is rejoined by the main part i_s of the current which flows through the left-hand half of the transformer winding. The corresponding current curves are shown in Fig. 7 at i_c and i_d. These currents flow in opposite directions through the two halves of S and their net effect is to produce the sinusoidal single-phase half-wave I_1. The other half-wave of I_1 is similarly produced during the next half-cycle when *II* is burning and *I* is blocked.

Power.—It now remains to explain how the constant-power line P_3 of three-phase input, Fig. 7, corresponds to the pulsating single-phase output P_1. The product of the voltage e_L and the constant current I_d gives the curve P_L of power stored by the choke L. As regards the condenser C, its current curve i_c is repeated in Fig. 7, superimposed on the curve of voltage between the points A, B, Fig. 6. The product of these two curves gives P_c, the power stored by the condenser. Adding the ordinates of P_L and P_c, we obtain the sinusoidal curve shown for the total power stored by the voltage and current smoothers. This stored power, in conjunction with the constant input P_3, produces the pulsating single-phase output P_1. In other words, if (P_L+P_c) be added to P_1 there is obtained a constant-power line as dotted, corresponding exactly to the three-phase input (losses are here neglected).

Wattless Power.—It is a special advantage of this system that only active, and no wattless power is drawn from the three-phase system. The condenser C not only acts as current smoother but also supplies wattless power, the wattless current flowing in the circuit indicated by the heavy lines in Fig. 6(*c*).

Tests carried out with the Brown Boveri phase and frequency converter have proved its capabilities in respect of symmetrical three-phase loading, high efficiency, sinusoidal single-phase voltage, nearly unity 3-phase power factor with wattless single-phase output as required by traction service, and, of course, the simplicity and flexibility of operation associated with grid control.

A different method is used in the 3,600 kVA. mercury converter built by the A.E.G. to the order of the German State Railway, for the purpose of converting 45 kV., three-

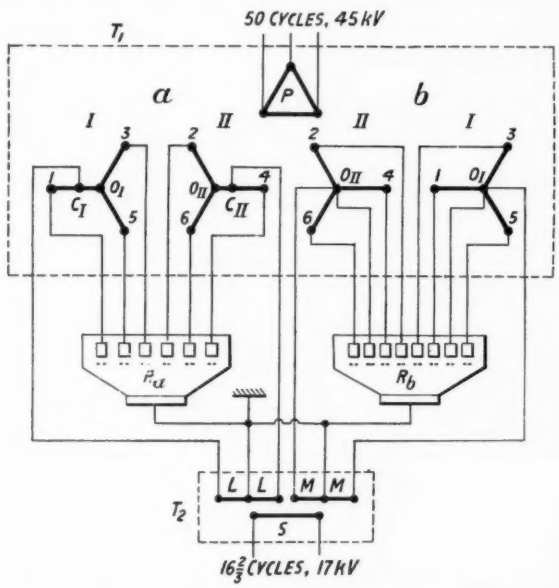


Fig. 8—Circuit diagram of A.E.G. phase and frequency converter for the Wiesental section of the German State Railway

phase, 50-cycle supply from the Rheinfelden transmission system to 17 kV., single-phase, $16\frac{2}{3}$ cycles, for the operation of the Basel-Schöpfheim-Zell-Säckingen electrified section of the Wiesentalbahn. This plant, which is the first of its kind in railway service, takes the place of rotary converter and buffer battery equipment hitherto employed. The connections and principle of operation are illustrated by the accompanying diagrams, Figs. 8 and 9. The secondary or single-phase voltage curve e_2, Fig. 9 is built up by the addition of three partial voltages e_a, e_b, e_c, this arrangement effecting a favourable utilisation of the anodes and transformer windings and producing a wave form which closely approximates to sinusoidal.

The primary P of the three-phase transformer T_1, Fig. 8, is fed with three-phase current at 45 kV., 50 cycles, and there are two pairs of secondary windings *I*, *II* connected to mercury converters R_a, R_b as shown. The curve e_a is derived from the group *a* of transformer windings and rectifier R_a, while the curve e_b is derived from group *b*, the figures and letters between the cusps in Fig. 9 indicating the group and phase from which each three-phase component is derived. The partial three-phase voltage e_c

is derived from the tappings c_I, c_{II} and superimposed directly on the voltage e_a. There is thus operative a voltage $(e_a + e_c)$ in the windings L, and e_b in the windings M, and these are combined to $e_2 = (e_a + e_b + e_c)$ by the transformer T_2, which also raises the resultant single-phase voltage to the desired voltage in the secondary winding S. A purely electrical system of grid control, without rotating switchgear, is so arranged that each anode passes the appropriate segment of a three-phase voltage curve.

This static converter equipment is rated for a continuous output of 3,600 kVA. single-phase at 0·6–0·7 power factor, and can supply 10 per cent. overload (4,000 kVA.) for $\frac{1}{2}$ hr. and 66 per cent. overload (6,000 kVA.) for one minute. The space occupied by the converter and three-phase transformer is only that formerly occupied by a 1,000 kVA. phase-advancer. A rotary converter equipment of equal capacity would occupy, without transformer, about four times the space occupied by the mercury converter, its transformer and auxiliaries. In addition, there are in new stations, the savings resulting from lighter foundations, smaller crane, and simplified automatic operation compared with rotating machinery. The efficiency of the mercury converter equipment is 90 per cent. at full load, 0·7 power factor, and 91 per cent. at half-load ; its annual average efficiency will be about 83 per cent., representing a saving of 19 per cent. compared with rotary equipment and 26 per cent. compared with the system hitherto employed.

In Fig. 10 is illustrated the installation of Brown-Boveri type rectifiers in a large substation on the Boné-Duvivier-Oued Keberit section of the Algerian State Railways, which is electrified on the 3,000 volt d.c. system. The 90 kV. transmission current passes through static transformers and enters the rectifiers as three-phase current at 5,500 volts, emerging as d.c. at the line pressure.

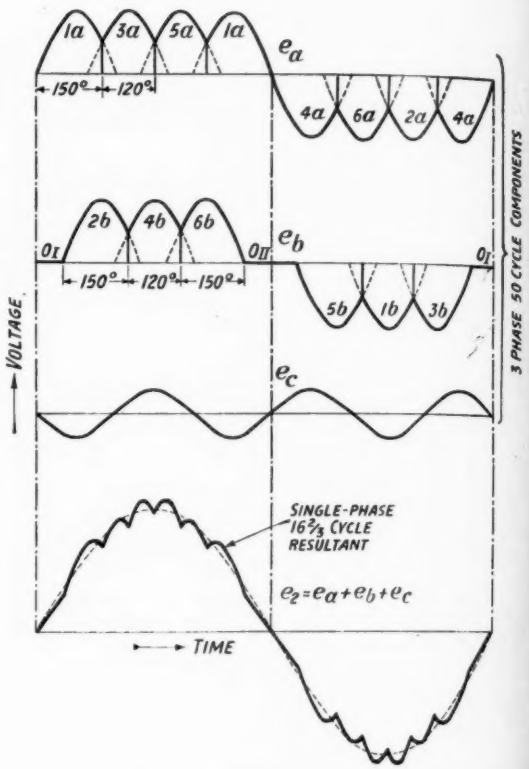


Fig. 9—Diagram showing the formation of 16⅔ cycle wave by the addition of three-phase 50-cycle components.

Fig. 10—Substation at Boné on the Algerian State Railways fitted with metal-clad mercury arc rectifiers supplied by the Cie. d'Entreprises Electro-Mecaniques of Paris. The rectifiers are of the Brown-Boveri type, rated at 2,000 k.W. and are referred to in this article

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3 PHASE 50 CYCLE COMPONENTS

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